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PERTURBATION THEORY FOR GENERALIZED FREDHOLM OPERATORS

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Successful development of the theory of Fredholm and semi-Fredholm operators and a general recognition of the importance of the subject provides an impetus for the study of various generalizations. In this paper, a study is made of operators whose ranges and null spaces are closed complemented subspaces. In particular, if T is such an operator, a rather general sufficient condition is obtained to ensure that $T - U$ is of the same kind. This perturbation theorem includes, as special cases, previous results due to Dieudonné, Saphar, and Crownover.

1. Definitions and basic properties. If X is a Banach space, write $B(X)$ to denote the space of continuous linear operators defined on X . We shall study the class of operators T in $B(X)$ which have the property that both the null space $N(T)$ and the range $R(T)$ are closed complemented subspaces of X . This class of operators contains all the Fredholm operators and will therefore be called the *generalized Fredholm operators*, denoted $GF(X)$. We observe immediately that when X is a Hilbert space, then $GF(X)$ consists merely of those operators which have closed range and that in all cases, $GF(X)$ contains all projections. Such an observation would discourage one's optimism about paralleling the theory of Fredholm operators to any reasonable extent. However, the fact that $GF(X)$ has already been studied under another guise encourages further scrutiny; more precisely, we introduce the notion of *generalized inverse* as follows: an operator T in $B(X)$ is said to have a generalized inverse S in $B(X)$ if the following equations are valid:

$$(1) \quad TST = T$$

$$(2) \quad STS = S.$$

The above notion has attracted a great deal of interest in the finite dimensional case and has been the subject of at least three recent monographs ([3], [8], [9]). It is perhaps appropriate to remark that conditions (1) and (2) are usually augmented by others leading to a variety of notions with a rather variable terminology. Some extensions to infinite dimensional situations have been considered by F. J. Beutler [2], and W. T. Reid [10] and others. Particular attention should be paid to the early paper of Atkinson [1] in which he calls operators satisfying (1) and (2) *relatively regular* and derives

many of their properties. The fact that generalized Fredholm operators are exactly those which have a generalized inverse has been known for a long time but since its proof is usually given in a finite dimensional setting, it is included here in the general case.

LEMMA. *T is a generalized Fredholm operator if and only if T has a generalized inverse.*

Proof. Let T belong to $GF(X)$ so that there exist closed subspaces X_1 and X_2 such that X can be decomposed as $N(T) \oplus X_1$ and $R(T) \oplus X_2$. Let P denote the projection onto $R(T)$ parallel to X_2 . Now write T_1 for the restriction of T to X_1 so that T_1 has a continuous inverse defined on $R(T)$. Therefore, $T_1^{-1}P$ is well defined in $B(X)$; it is easy to check that $T_1^{-1}P$ is a generalized inverse of T .

Conversely, if S is a generalized inverse of T , then equations (1) and (2) imply that TS is a projection of X onto $R(T)$ parallel to $N(S)$ and $I - ST$ is a projection of X onto $N(T)$ parallel to $R(S)$. Hence T belongs to $GF(X)$.

2. Perturbation theory. In general, $GF(X)$ is not an open set nor is it stable under compact perturbations. To see this, we recall a construction due to R. J. Whitley ([7], V.2.6): if T is an operator with closed range of infinite codimension and $N(T)$ is infinite dimensional, then it is possible to construct a compact operator B such that $T + \lambda B$ does not have closed range for any $\lambda \neq 0$. The perturbation problem which we study therefore, gives a sufficient condition on the operators concerned and our result will include various interesting special cases including those of Saphar [11] and Crownover [4].

THEOREM. *Let T be a generalized Fredholm operator defined on Banach space X and suppose that S is a generalized inverse of T . Let U be an operator in $B(X)$ such that $\|U\| < \|S\|^{-1}$ and $(I - US)^{-1}U$ maps $N(T)$ into $R(T)$. Then $S(I - US)^{-1}$ and $(I - SU)^{-1}S$ are equal and their common value V is a generalized inverse of $T - U$. Moreover, $N(T - U)$ is a complementary subspace to $R(S)$ and $R(T - U)$ is a complementary subspace to $N(S)$ so that $N(T - U)$ and $R(T - U)$ are linearly homeomorphic, respectively to $N(T)$ and $R(T)$.*

Proof. Since $\|U\| < \|S\|^{-1}$, the Neumann series of $(I - US)^{-1}$ and $(I - SU)^{-1}$ converge and it is easy to see, by writing them out, that $S(I - US)^{-1}$ and $(I - SU)^{-1}S$ are equal. Then

$$\begin{aligned}
 V(T - U)V &= (I - SU)^{-1}S(T - U)S(I - US)^{-1} \\
 &= (I - SU)^{-1}(STS - SUS)(I - US)^{-1} \\
 &= (I - SU)^{-1}S(I - US)(I - US)^{-1} \\
 &= V.
 \end{aligned}$$

Now consider

$$\begin{aligned}
 T - U - (T - U)V(T - U) &= [I - (T - U)S(I - US)^{-1}](T - U) \\
 &= [I - US - (T - U)S](I - US)^{-1}(T - U) \\
 &= (I - TS)(I - US)^{-1}(T - UST + UST - U) \\
 &= (I - TS)(I - US)^{-1}[(I - US)T + U(ST - I)] \\
 &= (I - TS)(I - US)^{-1}U(ST - I) \\
 &= 0
 \end{aligned}$$

if $(I - US)^{-1}U$ maps $R(ST - I)$ into $N(I - TS)$. But, as noted in the proof of the Lemma, $R(ST - I)$ is $N(T)$ and $N(I - TS)$ is $R(T)$. Hence the first part of the proof is complete.

Now

$$R(V) = R[S(I - US)^{-1}] = R(S)$$

so that

$$X = N(T - U) \oplus R(V) = N(T - U) \oplus R(S).$$

Similarly

$$N(V) = N[(I - SU)^{-1}S] = N(S)$$

so that

$$X = R(T - U) \oplus N(V) = R(T - U) \oplus N(S).$$

COROLLARIES. 1. If $N(U) \supseteq N(T)$ or $R(U) \subseteq R(T)$ with $\|U\| \leq \|S\|^{-1}$, then $T - U$ is generalized Fredholm.

Proof. If $N(U) \supseteq N(T)$, then $(I - US)^{-1}U$ maps $N(T)$ onto $\{0\}$. If $R(U) \subseteq R(T)$, then we observe that $(I - US)^{-1}U$ can be written as $U(I - SU)^{-1}$ so that its range lies inside $R(U)$ and hence it maps $N(T)$ into $R(T)$.

2. The class of left invertible operators is given by $\{T \in GF(X): N(T) = \{0\}\}$; the class of right invertible operators is given by $\{T \in GF(X): R(T) = X\}$. Hence from Corollary 1, we obtain the well-known result (Dieudonné [5]) that these classes are open sets in $B(X)$.

3. Suppose T is a generalized Fredholm operator with $R(T) \supseteq N(T)$. Let M be closed subspace of X such that $R(T) \supseteq M \supseteq N(T)$

and $TM = M$. Then if $UM \subseteq M$ and $\|U\| < \|S\|^{-1}$, the conclusions of the Theorem are valid.

Proof. $(TS)M = (TST)M = TM = M$ so that $SM \subseteq T^{-1}M$. Now if $m \in T^{-1}M$, then $Tm \in M = TM$ so that there exists $m' \in M$ such that $Tm = Tm'$. But $m - m' \in N(T) \subseteq M$ so that $m \in M$. Hence $T^{-1}M \subseteq M$. Therefore, $SM \subseteq M$ and so $(I - US)^{-1}UM \subseteq M$. Hence we can write

$$\begin{aligned} R[(I - TS)(I - US)^{-1}U(ST - I)] &= (I - TS)(I - US)^{-1}UN(T) \\ &\subseteq (I - TS)(I - US)^{-1}UM \\ &\subseteq (I - TS)M \\ &\subseteq (I - TS)R(T) = \{0\}. \end{aligned}$$

Hence the result.

4. If $R(T^n) \supseteq N(T)$ for each n and all $R(T^n)$ are closed, then $M = \bigcap_{n=1}^{\infty} R(T^n)$ satisfies the conditions of Corollary 3. This gives Saphar's main result in [11] (Théorèmes 1 and 2).

5. If $N(T) = \{0\}$ and $R(T)$ has codimension 1 (and is therefore closed) and $\bigcap_{n=1}^{\infty} R(T^n) = \{0\}$, then Crownover [3] calls such an operator a shift on X . Clearly, for any such shift, all $R(T^n)$ are closed since T is Fredholm. Therefore, shifts satisfy the condition of Corollary 4. Crownover's Theorem 2 ([4], p. 236) considers $T - \lambda I$ when T is a shift and derives a result essentially the same as ours in this very special case.

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